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Field tests on micropiles under dynamic lateral loading

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Abstract

Micropiles are increasingly used as foundation support of new buildings in seismic areas as well as for the seismic retrofitting of structures that have experienced seismic damage. Hence, it is essential to enhance the knowledge of the dynamic behavior of micropiles under horizontal loading. In the present paper, first steps of an extensive experimental study carried out on two vertical micropiles in alluvial silty soil are reported. One of the vertical micropiles is injected throughout valves a-manchèttes placed along the steel core of the shaft, while the other one is simply grouted. In particular, experimental results of ambient vibration tests and impact load tests are reported and a comparison between the behavior of the vertical injected and non-injected micropiles is provided. Experimental data of impact load tests are also compared with results obtained from an analytical model.
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Keywords: Experimental study; micropiles; soil-pile interaction; ambient vibration test; horizontal impact load test

1. Introduction

In the last decades, a lot of research effort has been put in the field of soil-pile dynamic interaction, as it can dramatically influence the dynamic response of the soil-foundation-structure system to horizontal dynamic loads (i.e. earthquakes). Accordingly, there is a need for experimental data from real scale tests, as they are extremely precious for the calibration of numerical or theoretical models adopted to investigate the problem. However, the state of the art on dynamic horizontal field study on deep foundations is poor [1-4] and various phenomena need further

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investigations, such as the role of execution stages and construction techniques. This point is particularly crucial in the case of micropiles. Micropiles are small-diameter cast-in-situ bored pile formed by cement grout injection and subsequently equipped with lost, steel reinforcement element. They are increasingly used as foundations of new constructions and to strengthen foundations of existing structures in seismic zones, thanks to their simplicity of execution. Despite their growing use, results from static and cyclic lateral load tests on micropiles are limited [5], and dynamic field tests data are almost absent; thus, an experimental campaign is carried out, that includes both two single vertical micropiles and a group of inclined micropiles. In the present paper results obtained from ambient vibration and lateral impact loading tests on the vertical micropiles are discussed. A comparison with an analytical model is also reported.

2. Description of the site and instrumented micropiles

The experimental field campaign is performed in alluvial silty deposit on IRS (Injection Répétitive et Sélective) micropiles. They are small diameter cast-in-situ bored piles formed by cement grout injection, equipped with a hollow-core steel bar and finally completed by multi-step high pressure grouting at predetermined depths via valves a manchèttes placed along the bar. In this study, the traditional execution stages were suitably modified to allow the preliminary instrumentation of the hollow-core steel bar of the micropiles, and to limit damages of the sensors induced by mechanical stresses during the in-situ installation and the high pressure injection stages.

2.1. Site Description

Micropiles are installed in an industrial zone nearby Ancona (central Italy). The geology of the area, which has a flat topography, is characterized by an alluvial deposits consisting predominantly of clayey and silty materials, placed above a Pliocene clay formation. A specific geotechnical investigation campaign was carried out including: 2 continuous vertical boreholes to a depth of 15 m, 2 static penetrometer tests (CPTs) to a depth of 20 m, and laboratory tests on undisturbed soil samples (volumetric characteristics, Atterberg limits, unconfined compression test, direct shear test, oedometer test, unconfined undrained triaxial test). Furthermore, the profile of the shear wave velocity V_s with depth and the fundamental period of the deposit have been evaluated from passive and active geophysical survey techniques (MASW, ESAC, HVSR). Details relevant to the stratigraphic model are shown in Figure 1a. The micropiles shafts are embedded in a quite homogeneous and normally consolidated alluvial silty-clayey layer with poor mechanical properties, characterized by V_s = 180 m/s. The water table is located about 3.5 m deep in the upper stratigraphic unit. The seismic bedrock is recognized at a depth of 75 m from the ground level.

2.2. Micropiles

Micropiles reinforcement is constituted by 8 m long steel pipe bars, assembled trough the junction of 4 elements (each element is 2 m in length). The outer diameter of the circular cross section of each pipe is 76.1 mm, and 6 mm thick. From the head of the micropiles, the 3rd and 4th elements are equipped with four 50 cm spaced valves a manchèttes for high pressure injections. The 4th element is also provided with a bottom plug for the grout injection at the micropile tip. Valves a manchèttes are realized by means of 2 small holes for each valve, covered by a rubber band that is fastened by steel rings welded at the valve end. Traditionally, elements are assembled in situ during the insertion of the hollow bar into the grouted borehole. In this experimental study, elements were assembled in lab to allow the proper installation of measuring devices along the pipe. Once the sensors were mounted and zealously protected, the pipes were transported in situ for the installation (Fig. 1b). Firstly, soil borings were made with a diameter of 170 cm and a length of 7.5 m. Then, after the first grouting of each borehole, the instrumented pipes were carefully inserted. The upper 50 cm of the pipes were left above the ground level to allow the execution of the lateral dynamic tests. After 48 hours from the first grouting, additional grout was injected via valves a manchèttes in one of the two vertical micropiles using a packer with double effect piston: when the packer was at the required depth, the grout was injected at a pressure of 6 ÷ 8 MPa. The cement slurry used for both the first and the secondary (selective) grouting has a water cement ratio of 0.5. In the sequel, the IRS micropile is referred to as P1, while the non-injected one as P2. A schematic view of the micropiles is depicted in Fig. 1c.

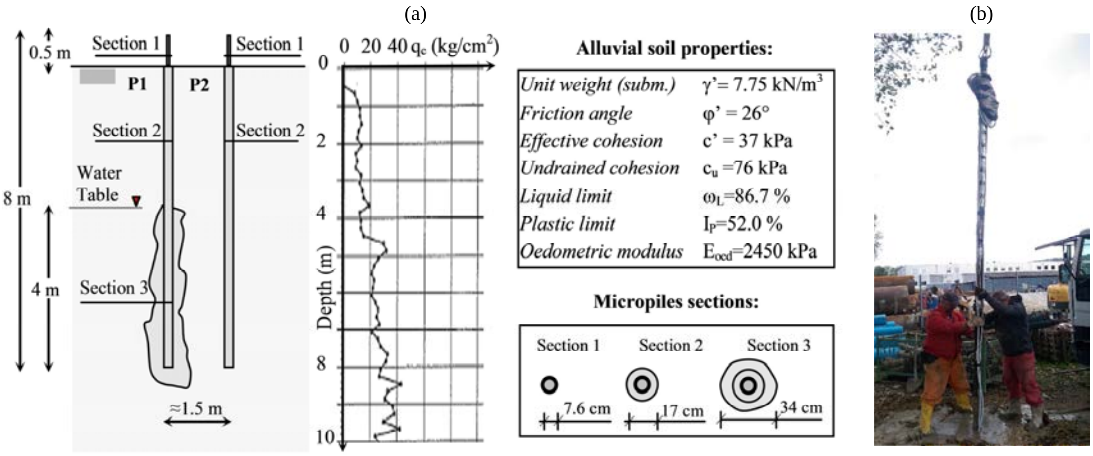


Fig. 1. a) Piles P1 and P2, CPT profile and mechanical properties of the alluvial layer; (b) Installation of an instrumented bar.

3. Instrumentation and tests setup

In order to investigate the dynamic response of micropiles characterized by different construction methods (more specifically by different method of grouting) both ambient vibration and lateral impact load tests are performed. Tests, performed before and after the execution of the injections, prove that most of the sensors still work after the installation of the instrumented steel core as well as after the high-pressure injections.

3.1. Instrumentation

In addition to the permanent instrumentation preliminarily installed on the steel core of the micropiles, other measuring devices are added at specific points during the tests. The measuring chains for the ambient vibration tests and the horizontal impact load tests differ, since the input and the output varies. For the ambient vibration tests the measuring chain includes two low noise piezoelectric accelerometers, connected to the power supply and acquisition system by means of low noise coaxial cables. Finally, a laptop with dedicated software is needed for processing and storing the signals. For the horizontal impact load tests the measuring chain consists of an instrumented large-sledge impulse hammer having a mass of 5.5 kg, equipped with a load cell; preliminary tests are performed to select the appropriate hammer tip so that the energy content of the spectrum excites the spectral contribution of the system. For the measuring of the horizontal acceleration at each micropile head, an uniaxial piezoelectric accelerometer is used. The chain also includes Strain Gauges (SGs), in order to measure the longitudinal strains along the shafts during the horizontal impact loading. In particular, the steel cores of the vertical micropiles are instrumented with 13 SGs along a main generatrix and with 2 SGs along two secondary verticals (17 SGs). The choice of the position of the sensors was suggested by the results of a preliminary soil-pile interaction analysis. T rosettes with two measuring grids connected in a half-bridge configuration are used in order to avoid the thermal effects. SGs are conditioned by means of a MGCplus that completes the full Wheatstone bridge, in order to amplify the strain gauges signal. Finally, the amplified signals are acquired by means of the same data acquisition system used for the impact load test. A big effort was done to protect sensor and cables against mechanical stresses induced by the high-pressure injections along the shaft of the steel core, as well as against aggressive agent (moisture and weathering above all). In particular, each SG is protected, both chemically and mechanically, with specific polyurethane paint and aluminium foil coupled with kneading compound; in addition, cables placed near valves a manchèttes are protected with high-resistance corrugated Polyethylene pipes. The accomplished precautions turned out to be effective, as most of the sensors kept on working properly after the high-pressure injections.

3.2. Ambient vibration tests

Ambient vibration tests allow investigating the dynamic response of full scale structures (bridges, buildings, dams, chimneys and silos, etc..) in the elastic range, by acquiring the response of the system to natural vibrations (e.g. anthropic activities noise, micro tremors, wind..). To the authors knowledge this procedure has never been adopted before to investigate the dynamic lateral behaviour of a simple soil-pile system. However, interesting information about the dynamic behaviour of the injected and non-injected micropiles are obtained. In this experimental campaign, two accelerometers per micropile are positioned on the pile head (i.e. measuring along two orthogonal axis called *x* and *y*). A time length of about 1500 seconds and a sample frequency of 2048 Hz are used for the tests. Signals are then suitably processed by means of traditional processing techniques (elimination of parts in which signal saturates, correction of the spurious trends, filtering, resampling).

3.3. Impact load tests

For this kind of test a pipe extension was rigidly connected at each micropile head in order to facilitate the execution of the impacts and the identification of the dynamic parameters. Two set of tests are performed: the first set (hereinafter referred to as SET 1) is characterized by a maximum force level of about 400 N in order to avoid the saturation of the accelerometer (at 10 g), while the second one (SET 2) by a higher force level in order to acquire the signal of strain gauges embedded in the soil. The present paper focuses on the results of SET 1, for which impulses are imparted along x and y orthogonal directions and the accelerometers are applied to the micropile so that the signal is acquired along the same direction of the impact. For SET 2, impacts are imparted along the direction relevant for the SG measurement (x for P1, y for P2). 10 impacts for each direction are imposed, in order to get a reliable averaged response. A sampling frequency of 2048 Hz is chosen to get high resolution in time domain, and an acquisition time duration of 2 s is considered, to investigate the entire duration of the micropile oscillation.

4. Results

Results of ambient vibration tests and impact vibration test performed after the micropiles installation are presented and discussed, paying attention to the influence of the high-pressure injection on the behavior of micropiles through a comparison between results obtained for P1 and P2.

4.1. Ambient vibration tests

Results of ambient vibration tests are here presented in terms of Power Spectral Density (PSD) function for P1 and P2 along x and y axis. From the superposition of *x* and *y* PSD functions for P1 (Fig. 4a) it appears clearly the dynamic behavior along the two orthogonal directions is substantially different, especially in terms of fundamental frequencies. On the other hand, results for P2 are very similar in the two directions (Fig. 4b). This fact can be attributed, at least partially, to the directionality of the high pressure injections executed on P1 since the two holes of each valve a manchèttes along the shaft were aligned along the y direction. This fact could have affected to some extent the dynamic response of P1, providing a greater stiffness of the soil-micropile system along the y direction.

4.2. Impact load tests

Results of impact load tests for SET 1 are here presented in terms of modulus of Frequency Response Function (FRF) of the registered acceleration at P1 and P2. Results refer to the averaged values obtained from 10 impacts. Coherently with results of the previous tests, the comparison of averaged FRFs obtained considering impacts along both directions (Fig. 5) shows that for the injected micropile a marked difference exists between the behaviour along the two direction (the pile seems stiffer along the y direction), especially for the second mode, while the non-injected micropile doesn’t show significant differences between the behaviour along the x axis and that along y axis.

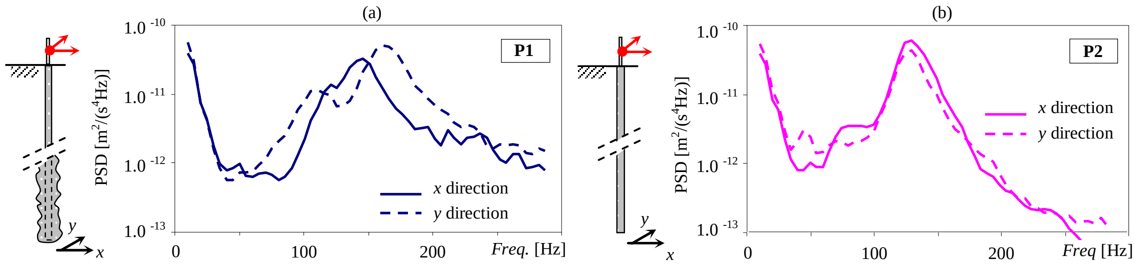


Fig. 2. PSD of acceleration registered along x and y axis during ambient vibration tests for (a) P1 and (b) P2.

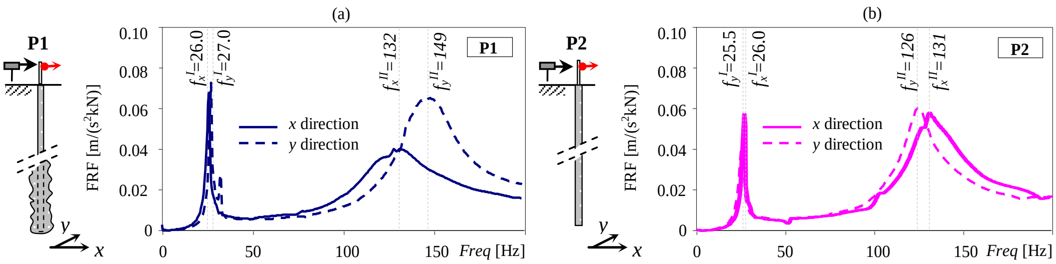


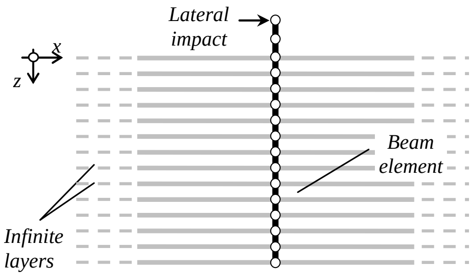
Fig. 3. FRF of acceleration along x and y axes during impact tests for P1 (a) and P2 (b).

5. Modeling

Experimental results obtained from the impact load tests are compared with those obtained from an analytical model, in order to reproduce the dynamic behavior of the soil-micropile system in the small-strain range, and to strengthen the interpretation of the associated phenomena. According to the analytical 3D model presented in [6] for the soil-pile system, the problem is handily formulated in the frequency domain, assuming that the micropile behaves linearly and considering the non linear behavior of the soil in a linear equivalent manner. Such assumptions can be accepted as long as the level of energy introduced in the system is low; this conditions can be considered satisfied in the case of impact load tests. As shown in Figure 4, piles are modelled as beam elements in the framework of a finite element approach, and the soil is considered as a visco-elastic medium consisting of infinite independent horizontal layers. The dynamics of each layer, which is a crucial aspect for the modelling of soil-structure interaction problem, is defined through elastodynamic Green's functions, which enable to catch automatically both radiation and hysteretic damping.

For the present application, the above described procedure was properly modified to take into account the peculiar loading conditions and the variations with depth of the cross section of the micropiles. Furthermore, the model has been calibrated to reproduce the experimental results obtained from the horizontal impact load tests. The injections are taken into account by considering an equivalent diameter evaluated on the basis of the volume of injected grout. Both soil and piles have been accurately discretized in order to catch the dynamic behavior in a sufficiently large range of frequencies.

Figure 5 shows the comparison in terms of FRF of acceleration at the micropile head for one of the impact load test performed on P1 and P2 along the x direction. A good accordance between the experimental and analytical data can be found for both the piles, up to more than 150 Hz (first and second vibration modes of the soil-pile system are correctly described). Therefore, it can be stated that the model is reasonably capable to catch the dynamic response of the system in the small strains range, in terms of fundamental frequency, damping and amplitude.



Soil properties	
Shear waves velocity, V_s	180 m/s
Density, ρ_s	17.75 kN/m^3
Material damping, ξ_s	*2 %*
Micropile properties	
Concrete elastic mod., E_c	22 GPa
Steel elastic mod., E_s	210 GPa

Fig. 4. Analytical model used to reproduce impact tests; and main properties of soil and micropile

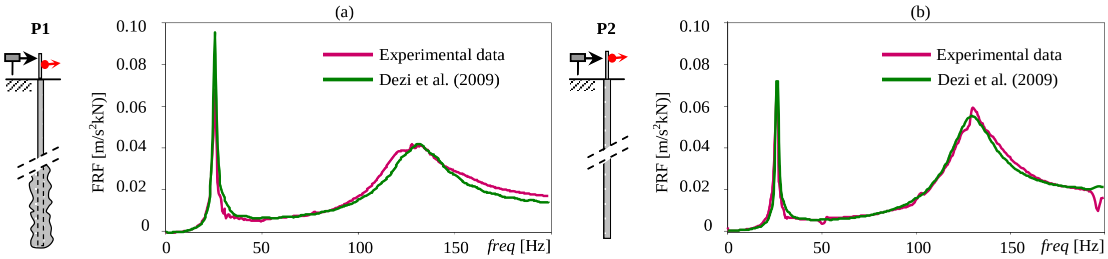


Fig. 5. Comparison between experimental and analitical results for one impact load (along x direction) on P1 (a) and P2 (b)

6. Conclusive remarks

In the present paper, first steps of an experimental study carried out on 2 vertical micropiles in alluvial silty soil are presented. After the installation, one of the two vertical micropiles was grouted with high pressure injections. Results of ambient vibration tests and horizontal impact load tests on the two micropiles reveal that high pressure injections visibly modifies the dynamic response at small strain, influencing the fundamental frequencies of the system and the directional behaviour. A comparison with the results of an analytical model is also carried out, proving the validity of that theoretical approach for the evaluation of the response of the soil-micropile system at small strain. In the coming months the field study will prosecute, in order to investigate the behaviour of the group of inclined IRS micropiles. Higher strain level will also be studied, and more complex modelling techniques will be adopted, trying to reproduce the non-linear behaviour of the system.

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